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BIOMONITORING IN CANADIAN FRESHWATERS:
THE DEPARTMENT OF FISHERIES AND OCEANS PROGRAMME

by

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Canada

A programme of biological monitoring of freshwaters has been developed by the Department of Fisheries and Oceans for use in assessing the long term effects of acidic deposition in five major geographic regions of Canada. Monitoring locations are distributed across a gradient in the sulphate depositional field, from the centre of the country to the extreme east coast. The programme operates in conjunction with air sampling and surface water chemistry monitoring programmes of the Department of the Environment. Over the next one or two decades monitoring will provide a long term data record on selected systems to demonstrate whether or not Canadian sulphur emission controls will lead to biological recovery in some presently impacted areas. Monitoring will also be able to document continued environmental deterioration in other parts of the country, and will help to establish expectations on the limits of natural variability in unaffected systems. The programme is aimed at establishing the community structure of the fish and littoral benthos components of aquatic systems. Annual assessment of most parameters is planned. Protocols have been developed for most activities and are being tested in 1987 prior to finalization. These protocols emphasize qualitative rather than quantitative sampling, with a view to establishing relative or categorical estimates of abundance. Details of the programme, the scientific basis for its structure and site selection criteria are given. Chironomid data from a monitorng programme conducted on an experimentally acidified lake and an adjacent reference lake in northwestern Ontario are used to illustrate the limitations and potential usefulness of some community analysis techniques for the preliminary interpretation of monitoring data.

For the past decade critics of North American acid rain studies have argued that direct proof of biological damage from acidic deposition is lacking (Roberts 1987). Considerable circumstantial evidence exists from surveys of water chemistry and biota in North America (Roff and Kwiatkowski 1977; Kelso et al. 1986) and in Europe (Økland 1980; Raddum 1980) to suggest that the restricted range of many species is highly correlated with the acidification of fresh waters. In only a few cases, though, have the direct effects of acidification on aquatic biota been documented (Allison and Harvey 1981; Watt et al. 1983; Schindler et al. 1984). Similarly, there is scant evidence of biological recovery from acidification effects in areas where deposition has lessened (Keller and Pitblado 1986).

Several Federal-Provincial agreements to reduce sulphur emissions in eastern Canada to 50% of 1980 levels have recently been signed. These reductions will be in full effect by 1994. Although it is expected that some parts of the province of Ontario will receive significant reductions in net sulphate deposition, the effect will diminish eastward to <5% reduction for the Maritimes, due largely to weather patterns and the presence of uncontrolled emission sources outside Canada. Thus, little improvement or a worsening of conditions is predicted for the eastern-most parts of the country, whereas some recovery is anticipated in central areas.

In response to the need to document any further environmental deterioration and to evaluate the effectiveness of emission control strategies, scientists with the Department of Fisheries and Oceans, working in conjunction with other government departments, have developed a programme of biological monitoring. The purpose of this paper is to outline the philosophy of that programme, comment on its perceived strengths and weaknesses, give essential details of the monitoring plan, and by way of example, illustrate

the potential usefulness of some techniques of community analysis for data interpretation.

A Pragmatic Philosophy of Biomonitoring

As a first principle of design it was recognized that a programme of biomonitoring must be scheduled to operate for several decades if long term trends were to be distinguished from the annual variability inherent in biological systems. The scope of the programme must also be limited both in areal coverage and in detail to assure its continuation regardless of future levels of funding. It was decided, therefore, that the monitoring effort be concentrated in a few specific areas across eastern Canada, distributed along a gradient in the sulphate depositional field. Further, candidate systems should be sensitive to the effects of acid deposition, co-located where possible with air and surface water chemical monitoring activities of the Department of the Environment, and sited within practical working distances of major research laboratories of the Department of Fisheries and Oceans.

A limitation imposed by this design was that it would not be possible to make regional extrapolations from the monitoring data gathered at specific sites. Differences in the zoogeographic distribution of species would make site-to-site comparisons difficult. It was also recognized that monitoring could not show cause and effect, only trends-through-time. However, monitoring results could serve as a catalyst for process-oriented research in each region, research which may provide the causal links and allow regional scale biological extrapolations to be made from observed changes in water chemistry.

Monitoring freshwater sports-fish in lakes and Atlantic salmon in the rivers of the east coast and along the north shore of the St. Lawrence River

was recognized as an activity of central importance to the programme because of the department's mandate to monitor and protect these resources. In addition, there was considerable evidence to suggest that many taxa including the Cyprinidae (Schindler et al. 1985), Crustacea and others (Nero and Schindler 1983; Eilers et al. 1984; Schindler et al. 1985; Stephenson and Mackie 1986; Økland and Økland 1986) are highly sensitive to acidification. Many of these taxa are considered to be "indicator species", but few are endemic to all parts of the country. Limiting the scope of sampling to sports fish and indicator species would restrict the usefulness of the data, particularly as they may apply to other environmental problems in the future, but complete characterization of lake or river biota on an annual basis would be beyond the capabilities of the programme participants.

As a compromise, a "select community" approach was adopted. Annual monitoring would consist of characterization of the total fish assemblage and the macrobenthic community (particularly in the littoral zone) of lakes, and the macrobenthos of riffle areas in rivers or streams along with supporting chemical, hydrological and habitat data.

The design of a monitoring programme for fish in rivers or streams proved more difficult than for lakes. First, most of the salmon rivers in Nova Scotia are supplemented with hatchery stock, making it impossible to evaluate "natural" community structure or year class success. Second, because rivers offer a wide range of habitat, it may be possible that large numbers of fish seek temporary refuge in relatively well buffered tributaries during periods of severe episodic pH depression in the main flow. Third, the migratory nature of fish stocks makes it difficult to ascertain their exposure history and diet, factors which are important for interpreting the results of biochemical tests that are currently being considered for use in the monitoring work.

As a solution to these problems, it was recommended that at all river locations, hatchery stock be held *in situ* in cages to give a practical assessment of water quality. In addition to providing a uniform method for each region, the cage bioassay could also supply fish with a known diet and exposure history for biochemical testing.

Monitoring Sites and Methods

Once the framework of the programme was in place, site selection criteria and sampling methods were developed. Five major monitoring areas were chosen (Fig. 1) consisting of lakes in the Experimental Lakes Area (ELA) northwestern Ontario (to serve as a low deposition reference site) and lakes in the Turkey Lakes Watershed, Algoma, Ontario, along with lakes and rivers in southern Quebec, southwestern Nova Scotia and southwestern Newfoundland. Within each area three to five candidate lakes or rivers that best fit a list of selection criteria were chosen.

Sets of lakes which were small (<50 ha), sensitive to the effects of acid deposition and contained both clear and brown-water systems were deemed suitable for monitoring. It was also desirable that one lake in each set have laminated sediments to allow paleolimnological work. Brown-water rivers with sustained low pH or clear-water rivers subject to episodic pH depression were sought in three of the five monitoring areas. Further requirements were that these rivers or streams contain salmon, sustain some minimum flow and had maximum flows in the study reach which did not preclude monitoring activities.

Four additional selection criteria were held in common among lakes and rivers. First, each system should contain biota which were representative of that part of the country. Second, monitoring sites should be reasonably accessible, but free of local pollution influence and relatively secure from

the possibility of future disturbance. Third, wherever possible, these systems should be co-located with the atmospheric and surface water chemistry monitoring sites of the Department of the Environment or provincial government agencies. Fourth, water levels should be gauged at each site so that discharge and water renewal times could be calculated, for the purpose of interpreting chemical data.

Development of a standard set of sampling methods began in 1986. These methods have undergone peer review and testing during 1987. Except for the fish cage bioassay and biochemical work which will be tested in 1988, sampling methods will be altered if necessary and finalized following the 1987 field season. In addition to standardizing the methods, common sets of sampling gear have been adopted for most activities to ensure uniformity of sampling technique. A summary of the target measurements, methods and suggested frequency of sampling is given in Table 1.

This basic programme was designed to give a broad annual characterization of the fish and macrobenthos of each system. Emphasis has been placed on determining community structure and the relative abundance of each taxon. Wherever quantitative data could be obtained for little or no increase in effort, that method has been used in preference to others, but for the most part, semi-quantitative or representative sampling methods have been adopted as the best compromise between information yield and cost.

The sampling activities outlined in Table 1 for 3-5 lakes or rivers in each area constitute the minimum acceptable programme. Participants are encouraged to monitor other relevant biotic factors, particularly those that are only specific to their geographic area or ones which they feel may make good candidate measurements for the overall programme. For example, zooplankton, phytoplankton and microbenthos sampling is not specified by this

protocol; nor is the use of a bioacoustic technique for measuring the standing stock of fish biomass. However, if a strong case can be made for any of these elements they may be included in the future.

Data Bases, Analysis and Reporting

No plans are being made to finalize the structure of a data base or devise standard analytical procedures until data from the first full year of the programme are available. Preliminary work on this activity will begin in 1988 using data from the test year of the programme.

Currently, there is general agreement that an exchange of data among programme participants is essential, though it is recognized that the primary responsibility for interpreting each data set rests with its originator. Computer storage and archiving of all information will be arranged at one central location. Mutual exchange of data and reports from the Canadian programme with those of other countries will also be welcomed, as will practical linkages between the various programmes.

An Example Community Analysis

Although it is relatively easy to detect changes in community structure brought about by the sudden appearance or disappearance of several major species or groups, these events usually have such catastrophic consequences that they seldom need full scale monitoring programmes to detect them. A more likely scenario for our monitoring programmes is that the data will show species shifts that are subtle, long term and clouded by annual variability. Detecting such changes is the real challenge of community analysis, a challenge which becomes progressively more difficult as the size of the information base increases. Working with large data sets usually precludes

the option of detailed inspection as a screening technique. Instead, the first stage of community analysis is often mathematical.

Despite the large array of techniques available for community analysis, the utility of most of them is often questioned (Washington 1984). Using several examples, I will illustrate how one of these methods has proven particularly powerful in identifying the effect of an experimental acidification on the structure of a chironomid (Diptera) community in a lake.

The acidification of a small (27.27 ha), oligotrophic Canadian Shield lake was begun in 1976 at the Experimental Lakes Area (ELA), northwestern Ontario. After two years of background study, weekly additions of sulphuric acid were made to the epilimnion of Lake 223 (L223) during the ice-free season each year. Slowly the pH of the lake was lowered from an initial value of about 6.50 to a minimum pH of 5.02 in 1981. Acidity was maintained at pH 5.09 in 1982 and at 5.13 in 1983. Details of the experimental treatment are given in Schindler et al. (1980) and Schindler et al. (1984).

From 1975 to 1983, I monitored the structure of the chironomid community in L223 by capturing adult insects in emergence traps, sampled weekly throughout each ice-free season. Traps were set out along transects according to an areally weighted scheme that sampled all depths with an effort that was directly proportional to the fraction of the total lake area occupied by each depth stratum. For reference, a similar sampling programme was conducted on nearby, non-acidified Lake 226SW (L226SW) from 1978 to 1986. Over the nine years that each lake was sampled, collections yielded a combined total of 154 species.

Preliminary analysis of the results showed that from 1981 to 1983 the total number of chironomid species in L223 fell to nearly half the original number (Fig. 2a). However, over the period from 1975 to 1983 there was little

change in the number of genera present in the lake from year-to-year. By comparison, the numbers of species and genera present in L226SW showed no consistent long term trend over a similar 9-year period (Fig. 2b). Annual variability in the number of genera present was higher for L226SW than for L223. The total species compliment of the L226SW community showed no trend, but did increase by almost 40% in one year (1981). Closer examination of the data showed that this increase was due to the presence of a greater number of moderately rare species (i.e. those whose abundances collectively totalled 1-5% of the overall emergence). 1981 was also the year in which total emergence in L226SW exceeded the mean value for all other years by 139%. Thus, total species number is in part a function of the number of individuals collected, particularly for the rare to moderately rare taxa, and as such, must be used with caution when interpreting change. It is important to note the relative insensitivity of the analysis at the generic level. This suggests that in any consideration of community structure it is desirable to pursue identifications to the species level, if possible.

Considerably more information on the changes brought about by the acidification became evident when the abundance of each species in the collection was ranked and the community divided into groups of common, moderately abundant, moderately rare, and rare species. In order, these groupings corresponded to the minimum number of species required to make up 50%, 51-95%, 96-99%, and >99% of total emergence. The data for L223 and L226SW, plotted as cumulative number of species in each category, are shown in Fig. 3a and Fig. 3b, respectively.

A steady decline in the number of species at all levels (i.e. common to rare) is apparent in the L223 data (Fig. 3a) from 1981 onward. The greatest decline was seen for rare species, but this result was due to the fact that

total emergence for the period 1981-1983 was much lower than average, so fewer rare species were sampled. Most significant is the reduction in the number of common species, from a value of 7-10 in the beginning years of the experiment, to only a single species of Cladotanytarsus by 1983. This suggests that if conditions were unfavourable for even common species, acidification may have caused a complete shift in the rank order abundance of individual taxa as well as an overall depletion in the number of species present.

Apart from a temporary increase in the number of moderately rare species in 1981, the data from L226SW (Fig. 3b) show no long term trend at any level. By using the data from L226SW as a reference, it can be concluded that the numerical balance of community structure should remain constant from year-to-year. Therefore, the changes seen in L223 from 1981 to 1983 lay outside the bounds of expected natural variability.

Diversity indices are commonly used as indicators of community change (Washington 1984). Two of these indices, Shannon-Weiner diversity (H') and Simpson's index (D), plotted as 1-D, are shown in Fig. 4 for L223 and L226SW. The formulae used to calculate these indices were:

$$H' = \sum_{i=1}^{S} \frac{ni}{n} \ln \frac{ni}{n}$$

and

$$D = \sum_{i=1}^{S} \frac{ni\ (ni-1)}{n\ (n-1)}$$

where n = the total number of individuals in the sample

ni = the number of individuals in the ith species category of the sample

s = the number of species in the sample.

In all cases, the indices show low annual variability. For L223 (Fig. 4a) Simpson's index gives little evidence of community change until 1983, whereas a steady downward trend in the Shannon-Weiner diversity index from 1980 to 1983 suggests that as early as 1980, shifts in community structure had begun to occur. Corresponding plots for L226SW (Fig. 4b) showed no trends. Because of their one-dimensional character, these indices contain little more information.

Unlike Shannon-Wiener diversity or Simpson's index which are easily confounded by species substitutions, Nometric Multidimensional Scaling (MDS) is sensitive to these species shifts (Kenkel and Orlóci 1986). MDS may be used to express community structure in each year as a set of point coordinates in two or three dimensional space. Thus, annual changes in species composition or abundance generate shifts among the points, both in their relative position and in the distances between them. The dimensional axes and their units simply reflect primary, secondary and tertiary measures of similarity or dissimilarity among communities, and do not readily correspond to any physical attributes of those species assemblages.

In the following example, I have analyzed the data from all years for L223 and L226SW as a combined unit so that dimensions produced by MDS, though arbitrary in meaning, were common to both sets of lake data. Due to space limitations in the computer and the program (SYSTAT), only 125 of the most common species from the combined total of 154 species were used. It is unlikely that eliminating the 29 rarest species altered the results of the analysis since most of these species showed only single occurrences in one of the two lakes.

A correlation matrix of Kendall's Tau-B coefficients was first calculated from the matrix of original abundance data (i.e. species vs lake/year) to give a relative measure of the degree of community similarity from year-to-year. Because Tau-B is a non-parametric statistic, it is well suited to this type of calculation, especially when monitoring data reflect only relative or categorical abundance. Further, with Tau-B, there is no need to transform data to meet the assumptions of normality, required by some other measures of correlation.

Using the matrix of Tau-B coefficients, MDS generated sets of point coordinates for each lake/year combination that best represented the interrelations among communities that were detailed in the correlation matrix. The scaling process itself is an iterative one that seeks a best fit solution. The results of the MDS analysis are shown as three-dimensional plots in Fig. 5.

These plots illustrate four important features of community change. First, points for L223 (Fig. 5a) were more widely dispersed (200% more in dimension 1, 40% more in dimension 2 and 14% more in dimension 3) than those for L226SW (Fig. 5b), indicating that long term variability was highest in L223. Second, changes for L226SW appeared to oscillate around a central tendency in a random fashion. Presumably, this random movement is an indication of natural variability. By contrast, the points for L223 fell along an S-shaped trajectory, a pattern which suggests directed change brought about by the acidification. Related to this is a third observation, that change in the L226SW plot was indicated almost entirely by movement in the second and third dimensions, whereas for L223 there was also considerable movement in dimension one. Thus, movement within dimensions two and three appeared to represent annual variability, whereas movement in dimension one implied a treatment effect. A fourth and final piece of information is

illustrated in Fig. 5a. By 1981, the pattern of directed change appeared to be well established for L223, but the way in which points for 1979, 1980 and 1981 were grouped in dimension 3 suggested that some shifts in community structure may have begun to occur as early as 1979. Previous methods gave no indication of such a change. An examination of the raw data showed that in 1979 some of the minor species (ones which eventually became dominant) were already beginning to increase in abundance while other, more common species, were starting to become rarer.

Although interpreting the significance of community change ultimately requires a detailed examination of species lists and temporal trends, MDS promises to be a sensitive and powerful technique for the preliminary screening of large volumes of data of the type that will likely be generated by biomonitoring programmes.

The success of any monitoring effort requires more than just routine sampling and periodic data analysis. Any commitment to monitoring must be long term and kept alive by assured levels of funding and technical support. Programmes themselves must evolve. For example, monitoring should contain a research component or be closely allied with research work. Data from monitoring will help to identify research questions. New or more sensitive techniques developed through research should be incorporated into monitoring programmes, provided that these additions do not jeopardize data continuity. It is important that methods and results be shared among different programmes, both within and between countries to enhance the sensitivity of measurement and data interpretation. An additional advantage to such cooperative programmes is that by the very nature of their multidisciplinary or international character, they tend to ensure the survival of each of the component studies.

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Figure 2. Abundance of species and genera in annual chironomid emergence collections from a) Lake 223, b) Lake 226SW.

Figure 3. Minimum number of species required to make up 50%, 95%, 99%, and 100% of the total annual standing crop of chironomid emergence in a) Lake 223, b) Lake 226SW. Species groupings based on abundance were as follows: 0-50% common, 50-95% moderately abundant, 95-99% moderately rare, and 99-100% rare.

Figure 4. Changes in annual chironomid diversity in a) Lake 223, b) Lake 226SW.

Figure 5. Three dimensional plots of the output from a nonmetric multidimensional scaling analysis of chironomid community structures in a) Lake 223, b) Lake 226SW. Point position indicates relative similarity among communities. Points are labelled according to year.

System	Component	Activity	Target	Method	Minimum frequency
Lake/river	Chemistry	Surface water sampling	pH, Gran alkalinity, major ions	DOE protocol and methods	3-5 times annually
Lake/river	Hydrology	Gauging and discharge	Water budget	Periodic measurement or weir	As required
Lake	Fish	Survey	Community composition and age class structure (all species)	Trap nets, gill nets, traps, seines	Annually to every 2-3 y depending on longevity
Lake	Fish	Survey	Community composition presence/absence (all species)	Trap nets, gill nets, traps, seines	Annual
River/lake	Fish	Bioassay*	Lethality test	Cage containment of test stock (50 d)	Once every 2-3 y
River/lake	Fish	Blood/tissue* sampling	Biochemical indicators	Under development	Once every 2-3 y in conjunction with bioassay
Lake	Macrobenthos	Littoral zone sampling	Crustaceans and insects	Hand collecting, sweep net, wire strainer (5 sites/lake)	Annual
Lake	Macrobenthos	Littoral zone sampling	Crayfish, leeches and misc. biota	Baited minnow traps (10)	Annual
Lake	Macrobenthos	Profundal sampling	Mysis, benthic crustaceans, Chironomidae	Dredge (5), vertical net tow (3 at night)	Annual
River	Macrobenthos	Riffle and bank sampling	Insects and crustaceans	Surber, wire strainer and hand collections (2 sites/river)	2-3 times annually
Lake/river	Vegetation	Survey	Mosses and filamentous algae (lake), canopy cover (rivers)	Inspection/photographic record	Annual
Lake	Paleolimnology	Sediment core sampling	Diatom frustules and other fossils	Sectioning and microscopic examination	Once during the early years

* Proposed monitoring

Table 1.

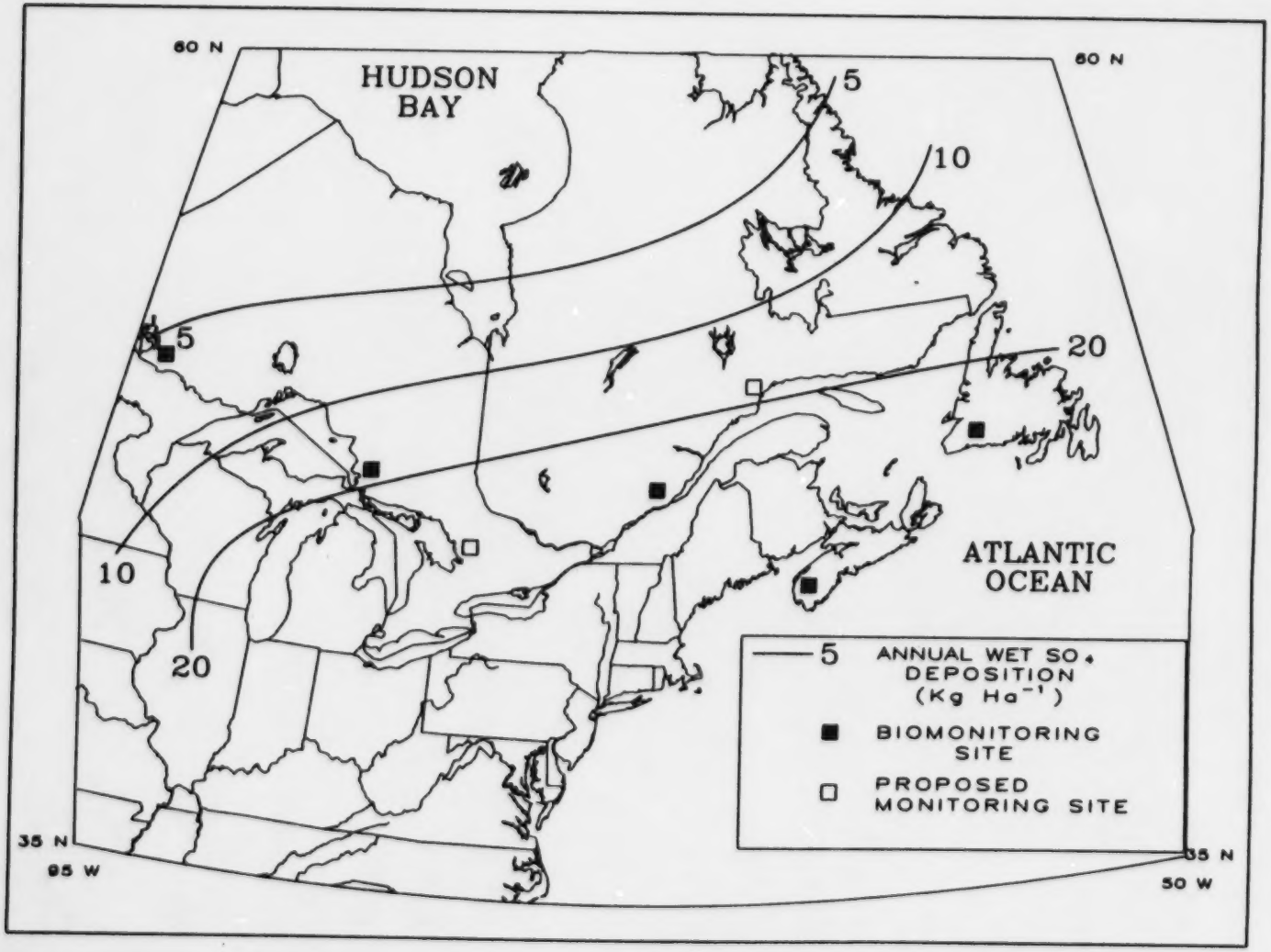
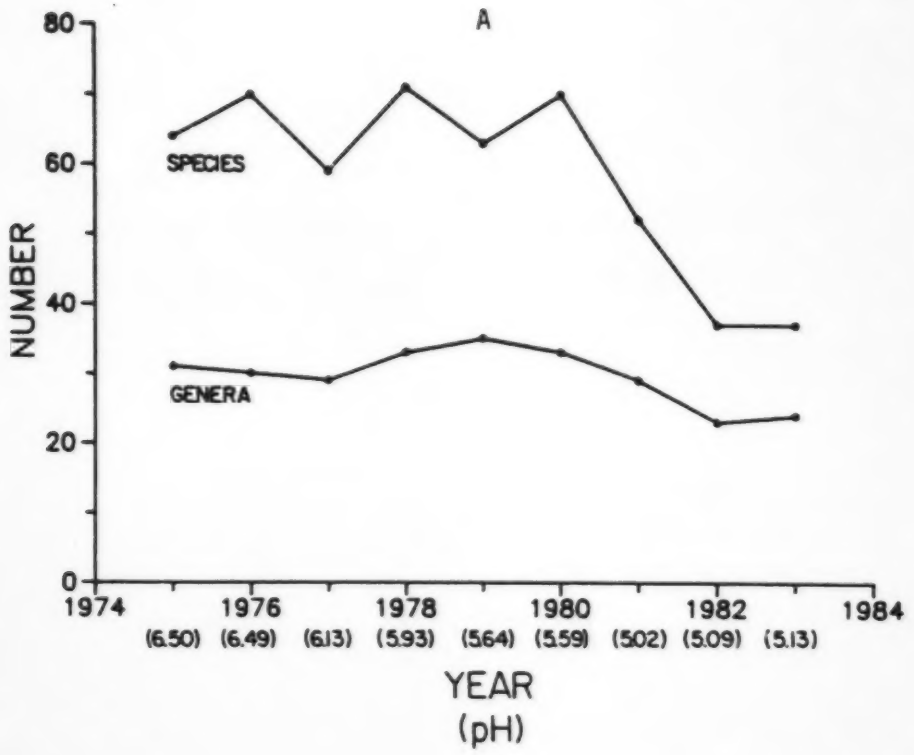

60 N
60 N
HUDSON
BAY
5
10
20
5
10
20
ATLANTIC
OCEAN
5 ANNUAL WET SO4 DEPOSITION (Kg Ha⁻¹)
BIOMONITORING SITE
PROPOSED MONITORING SITE
35 N
95 W
35 N
50 W

Figure 1.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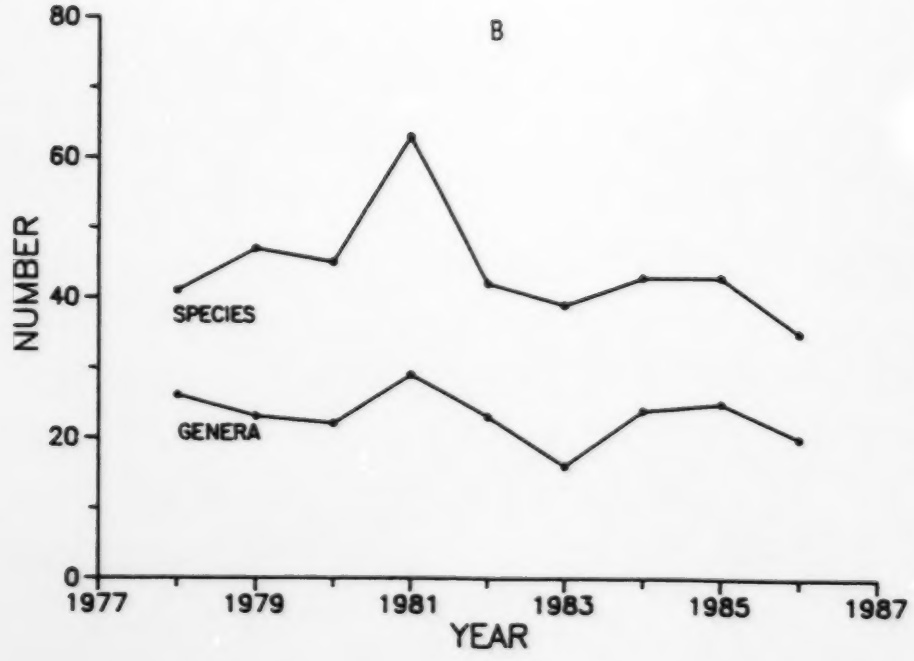
YEAR
(pH)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NUMBER
SPECIES
GENERA
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1981
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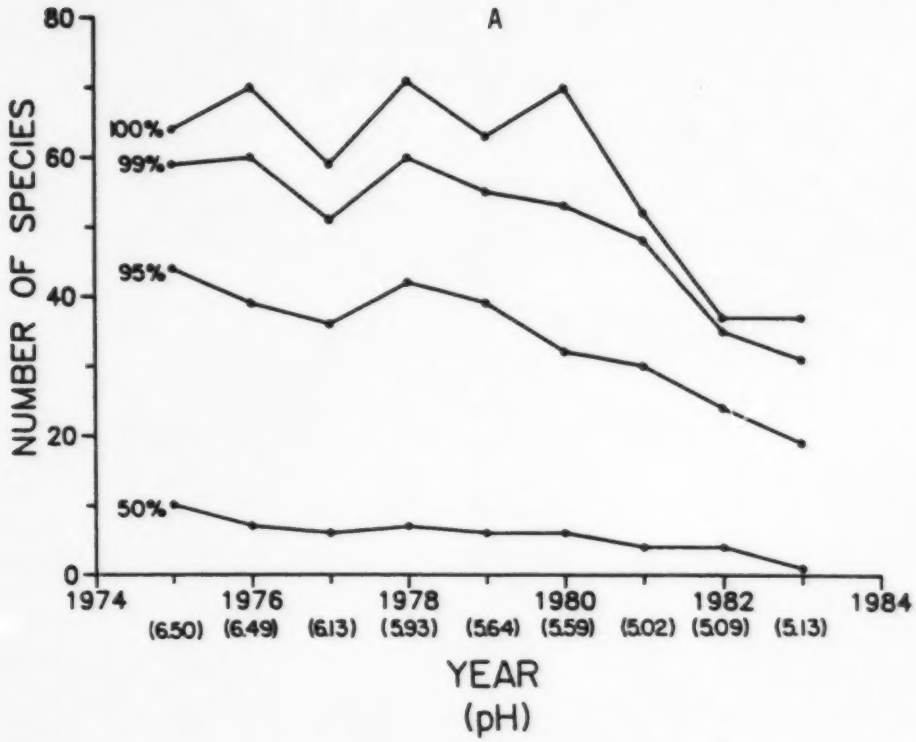
1985
1987
YEAR

Figure 2.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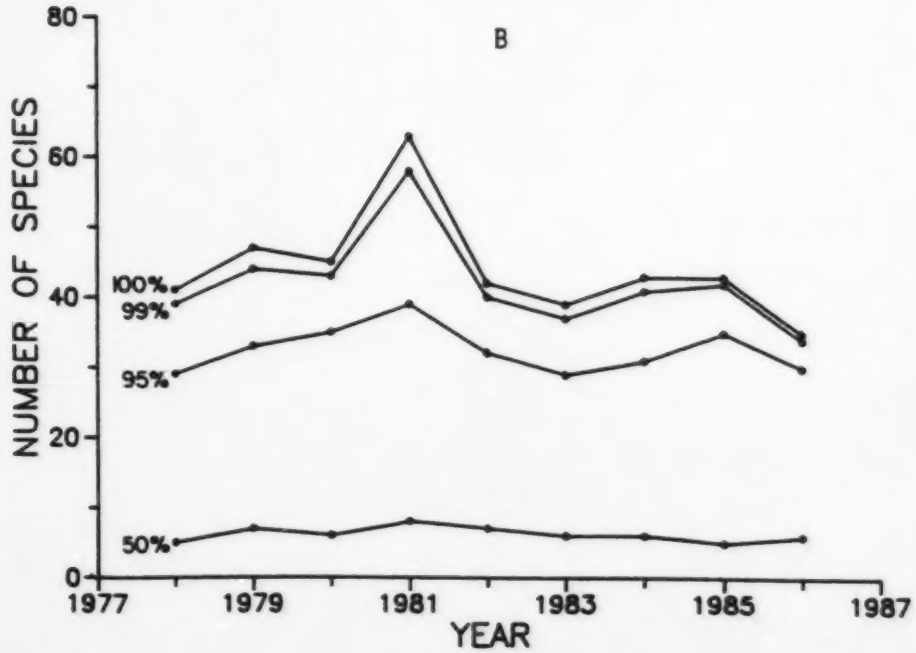
YEAR
(pH)


B
80
60
40
20
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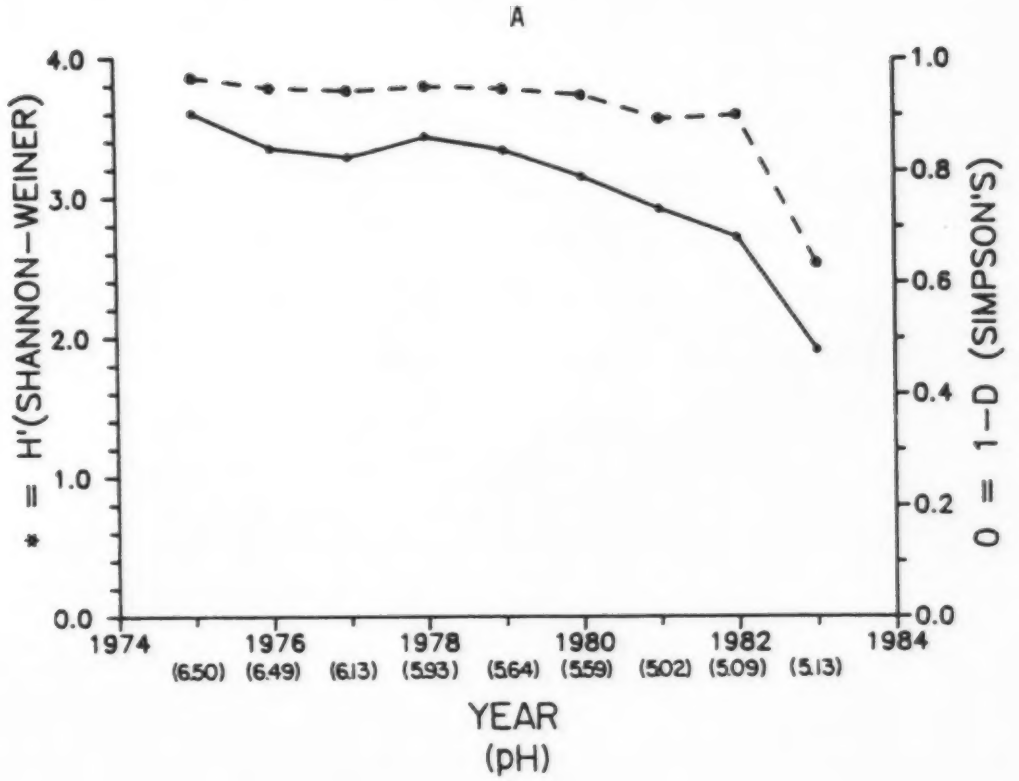
NUMBER OF SPECIES
100%
99%
95%
50%
1977
1979
1981
1983
1985
1987
YEAR

Figure 3.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3.0
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1.0
0.0
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0.8
0.6
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0.2
0.0
0 = 1-D (SIMPSON'S)
1974
1976
1978
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1982
1984
(6.50) (6.49) (6.13) (5.93) (5.64) (5.59) (5.02) (5.09) (5.13)
YEAR
(pH)

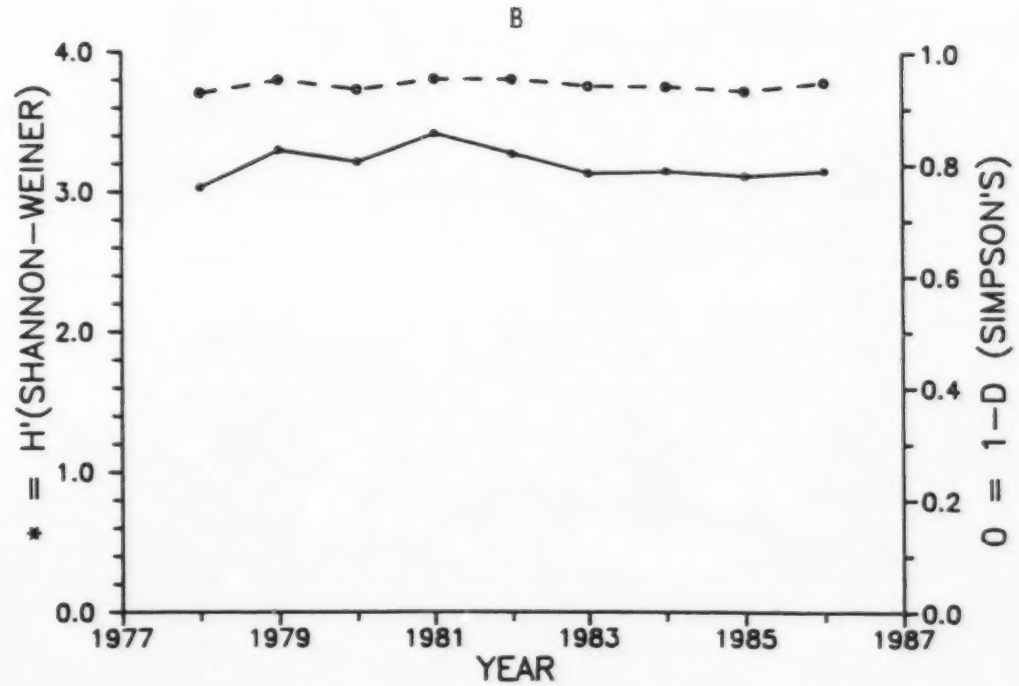
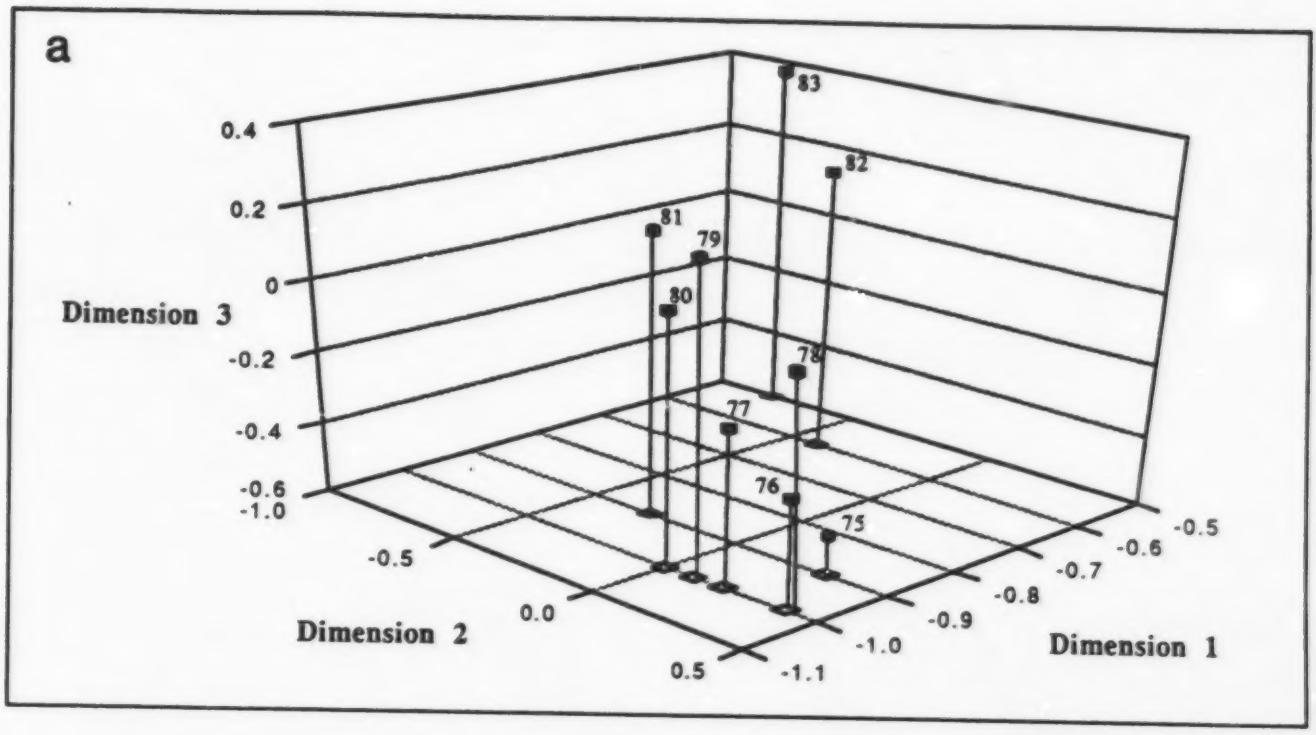

B
4.0
3.0
2.0
1.0
0.0
* = H'(SHANNON-WEINER)
1.0
0.8
0.6
0.4
0.2
0.0
0 = 1-D (SIMPSON'S)
1977
1979
1981
1983
1985
1987
YEAR

Figure 4.


a
Dimension 3
0.4
0.2
0
-0.2
-0.4
-0.6
-1.0
-0.5
0.0
0.5
Dimension 2
-1.1
-1.0
-0.9
-0.8
-0.7
-0.6
-0.5
Dimension 1
83
82
81
79
80
78
77
76
75

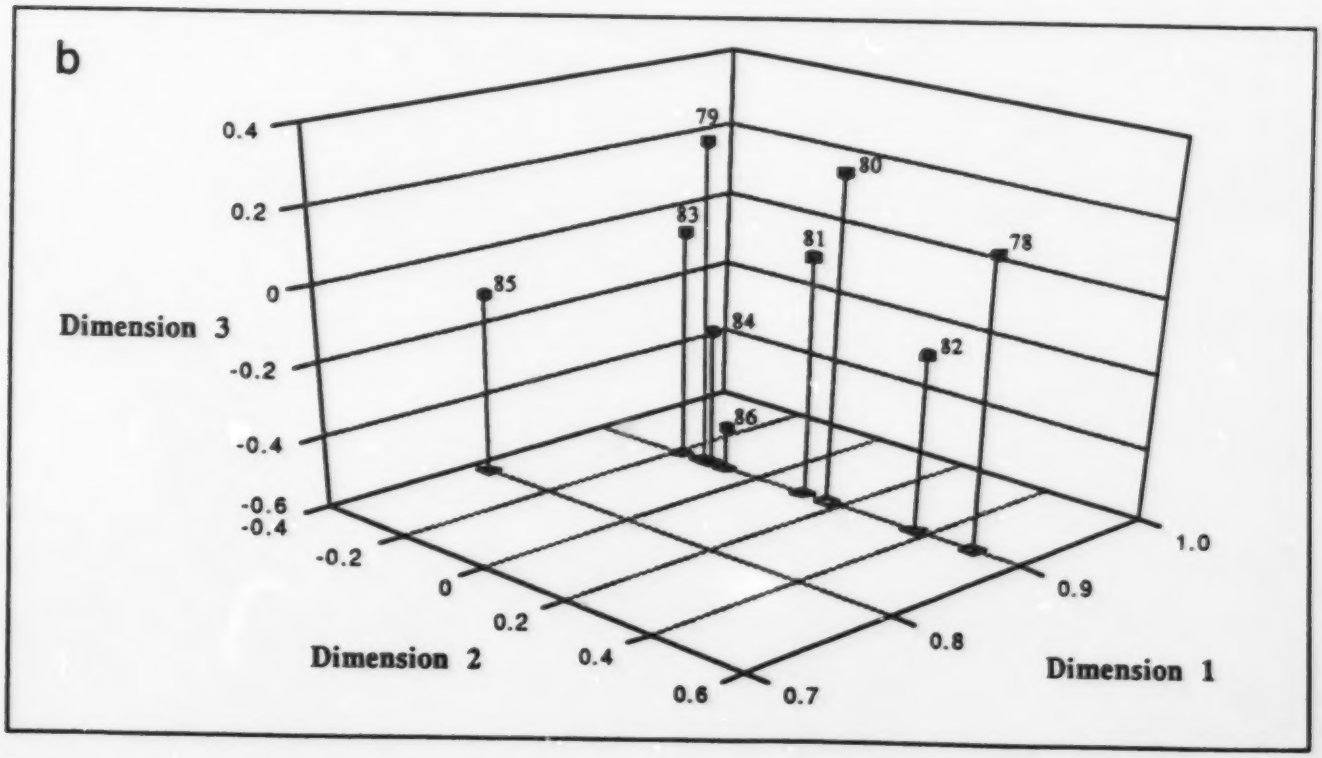

b
Dimension 3
0.4
0.2
0
-0.2
-0.4
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Dimension 2
0.7
0.8
0.9
1.0
Dimension 1
79
80
83
81
78
85
84
82
86

Figure 5.